LETTER

doi:10.1038/nature11787

Probabilistic cost estimates for climate change mitigation

Joeri Rogelj[1,2], David L. McCollum[2], Andy Reisinger[3], Malte Meinshausen[4,5] & Keywan Riahi[2,6]

For more than a decade, the target of keeping global warming below 2 °C has been a key focus of the international climate debate[1]. In response, the scientific community has published a number of scenario studies that estimate the costs of achieving such a target[2–5]. Producing these estimates remains a challenge, particularly because of relatively well known, but poorly quantified, uncertainties, and owing to limited integration of scientific knowledge across disciplines[6]. The integrated assessment community, on the one hand, has extensively assessed the influence of technological and socio-economic uncertainties on low-carbon scenarios and associated costs[2–4,7]. The climate modelling community, on the other hand, has spent years improving its understanding of the geophysical response of the Earth system to emissions of greenhouse gases[8–12]. This geophysical response remains a key uncertainty in the cost of mitigation scenarios but has been integrated with assessments of other uncertainties in only a rudimentary manner, that is, for equilibrium conditions[6,13]. Here we bridge this gap between the two research communities by generating distributions of the costs associated with limiting transient global temperature increase to below specific values, taking into account uncertainties in four factors: geophysical, technological, social and political. We find that political choices that delay mitigation have the largest effect on the cost–risk distribution, followed by geophysical uncertainties, social factors influencing future energy demand and, lastly, technological uncertainties surrounding the availability of greenhouse gas mitigation options. Our information on temperature risk and mitigation costs provides crucial information for policy-making, because it clarifies the relative importance of mitigation costs, energy demand and the timing of global action in reducing the risk of exceeding a global temperature increase of 2 °C, or other limits such as 3 °C or 1.5 °C, across a wide range of scenarios.

We generate cost distributions by combining mitigation cost estimates of emissions scenarios with probabilistic temperature projections. Importantly, our cost estimates do not account for any avoided climate damages as a result of emission reductions. This information is obtained from a large set of scenarios created with an integrated assessment model[14,15], for which the temperature increase is computed with a probabilistic climate model[16,17] (Fig. 1, Supplementary Fig. 1, Methods and Supplementary Information). Each modelling framework has inherent limitations. For example, although it incorporates state-of-the-art uncertainty quantifications of the Earth system, our model does not fully explore tipping points. Similarly our energy-economic emissions scenarios map a wide range of possible futures (Supplementary Figs 7 and 8) but are not exhaustive of all potential outcomes (Supplementary Information).

Temperature projections for any given pathway have a spread owing to geophysical uncertainties[18] (Fig. 1b). In the absence of any serious mitigation efforts (present global carbon prices of less than US\$1 per tonne of carbon-dioxide-equivalent emissions ($\mathrm{tCO_2e^{-1}}$)), the likelihood of limiting warming to less than 2 °C is essentially zero (<1%; Fig. 1c). However, imposing a carbon price of about US\$20 $\mathrm{tCO_2e^{-1}}$ in our model would increase the probability of staying below 2 °C to about 50%, and carbon prices of more than US\$40 $\mathrm{tCO_2e^{-1}}$ would achieve the 2 °C objective with a probability of more than 66% ('likely' by the definition of the Intergovernmental Panel on Climate Change[19]). Similar trends hold for other cost metrics (Supplementary Information). For example, a carbon price of US\$20–40 $\mathrm{tCO_2e^{-1}}$ translates in our model to cumulative discounted mitigation costs (2012–2100) of the order of 0.8–1.3% of gross world product (Supplementary Fig. 10).

A marked feature of the mitigation cost distribution (Fig. 2) is that the probability of global warming staying below 2 °C levels off at high carbon prices. This occurs because, beyond a given carbon price, nearly all mitigation options that can substantially influence emissions in the medium term have been deployed in our model. Higher carbon prices help further to reduce emissions later in the century, but only affect temperatures after peaking[20]. Hence, the probability of staying below 2 °C during the twenty-first century reaches an asymptote.

Geophysical uncertainties shed light on only one aspect of mitigation costs, however. To gain insight into how assumptions regarding technological and social uncertainties influence our cost distribution, we create a large set of sensitivity cases (Table 1), in which we vary some salient features of the scenarios, namely the availability and use of specific mitigation technologies; future social development and, by extension, global energy demand; and the international political context surrounding climate mitigation action, specifically delays in the implementation of a globally comprehensive mitigation response[7] (Supplementary Information). We note that population and economic growth do not vary in our scenarios; we therefore cannot assess their relative importance with our ensemble (Supplementary Information). Given its policy relevance[21], we focus most of our discussion on the limit of 2 °C (Supplementary Figs 4 and 5 illustrate the results for 2.5 and 3 °C, respectively).

Our results can be framed in two ways (Fig. 2): first, in terms of how probabilities for achieving the 2 °C objective change for a fixed cost (black arrows); and, second, in terms of how the cost consistent with the 2 °C goal varies for a given probability level (orange arrows). Whether or not a carbon price of about US\$40 $\mathrm{tCO_2e^{-1}}$ restricts global warming to less than 2 °C with a likelihood of more than 66% depends on the future availability of key mitigation technologies (Fig. 2a). In our worst-case technology-sensitivity assumption—that capture and geological storage of carbon (CCS) is entirely unavailable—the probability of staying below 2 °C at a carbon price of US\$40 $\mathrm{tCO_2e^{-1}}$ decreases to around 50%. However, with no such constraints and further technological breakthroughs (Table 1), the likelihood of limiting warming to 2 °C could be higher than 66% at the same carbon price.

The cost distributions also show how changes in technological measures affect the economics of mitigation given a fixed probability level. For example, in most cases the 2 °C objective can be achieved with a probability of more than 66% as long as the carbon price is high

---

[1] Institute for Atmospheric and Climate Science, ETH Zurich, Universitätstrasse 16, CH-8092 Zürich, Switzerland. [2] International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, A-2361 Laxenburg, Austria. [3] New Zealand Agricultural Greenhouse Gas Research Centre, Private Bag 11008, Palmerston North 4442, New Zealand. [4] School of Earth Sciences, University of Melbourne, Victoria 3010, Australia. [5] PRIMAP Group, Potsdam Institute for Climate Impact Research, PO Box 60 12 03, 14412 Potsdam, Germany. [6] Graz University of Technology, Inffeldgasse, A-8010 Graz, Austria.

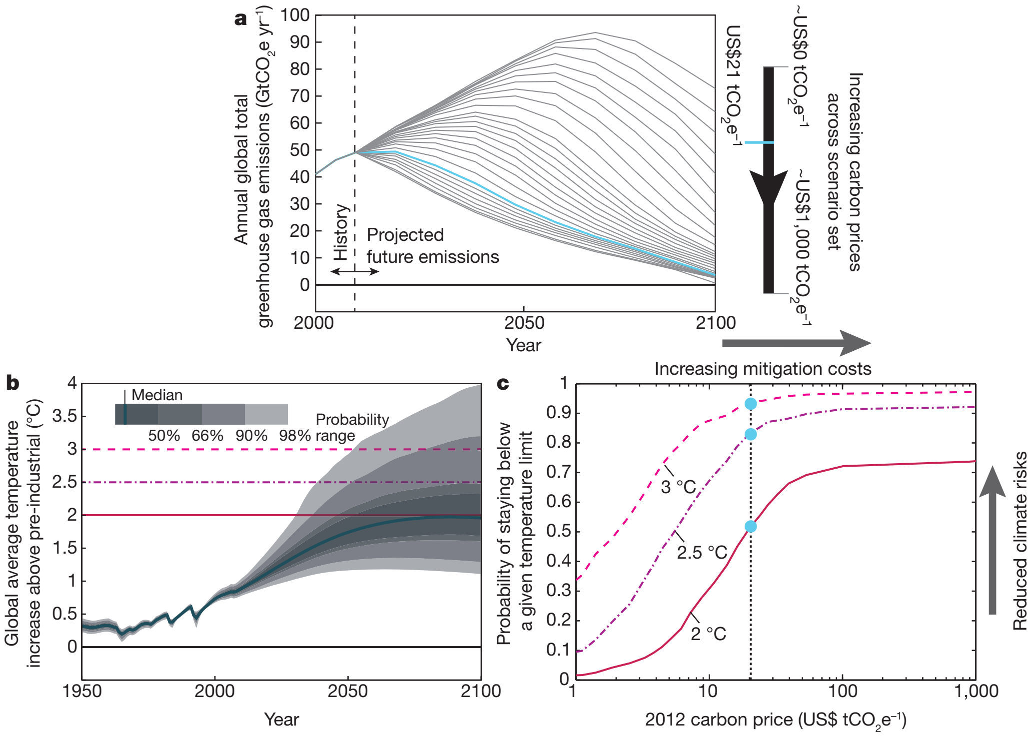

Figure 1 | Methodology for creating cost–risk relationships for a given temperature limit. **a**, Illustrative set of emissions scenarios with carbon prices increasing from zero to US\$1,000 tCO$_2$e^{-1}. The arrow at right indicates the direction of increasing carbon prices across the illustrative set. The blue-highlighted scenario has a global carbon price discounted back to 2012 of US\$21 tCO$_2$e^{-1}. **b**, Probabilistic temperature projections for the blue trajectory in **a**. Horizontal lines at 2, 2.5 and 3 °C show possible target temperature limits. In this illustrative scenario, median (50% probability) warming is 2.0 °C. There is a slim chance (<5%) that temperatures remain below 1.3 °C and a large chance (>90%) that they remain below 3.0 °C. **c**, Cumulative distributions of carbon prices consistent with limiting warming to below 2, 2.5 and 3 °C, as indicated. Blue dots indicate points defined by the cost information of the scenario highlighted in **a** and the probabilistic temperature projection in **b**.

enough (Fig. 2a). In certain instances, however, the lack of mitigation options (such as renewable technologies, nuclear power or limited biomass and afforestation potential) could require substantially higher carbon prices to keep this target viable. At the limit is CCS: the complete elimination of this mitigation option—either for technological reasons or as a result of social and political concerns—would put the 2 °C objective (with more than 66% probability) out of reach in our model, no matter how high the carbon price.

The future availability of energy supply technologies (for example renewable technologies and CCS) tells only one side of the story; a strong finding from our analysis is that social developments influencing energy demand (that is, efficiency of energy use) are even more important. This is evidenced in Fig. 2b by the differences between three distinct scenario families whose future energy demands vary greatly (low, intermediate and high; see Table 1 and ref. 7 for details). In the low-demand scenarios, end-use efficiency measures and conservation-minded energy and urban planning policies are instituted ubiquitously throughout the industrial, building and transportation sectors in all countries. This leads to a global energy demand in 2050 that is about 25% lower than our intermediate baseline, which broadly applies historical patterns of efficiency improvement[7]. Such reductions in demand could be crucial in keeping the 2 °C objective within reach, independently of what happens in terms of energy supply.

For example, in our scenarios the availability of nuclear power has an almost negligible effect on overall mitigation costs compared with a switch from a scenario with an intermediate energy demand to one with a high demand. Low-demand strategies would ensure a higher likelihood of staying below 2 °C for the same carbon price (from 66% to more than 80% at US\$40 tCO$_2$e^{-1}), or, viewed in a different way, would drastically reduce the cost of reaching the 'likely'[19] probability level (from US\$40 tCO$_2$e^{-1} to around US\$10–15 tCO$_2$e^{-1}). In contrast, a high-energy-demand future—about 20% greater in 2050 than the intermediate baseline, resulting from more energy-intensive lifestyles and less efficiency- and conservation-focused policies—would require much higher carbon prices (>US\$150 tCO$_2$e^{-1}) and make it much more difficult, if not impossible, to reach the 2 °C objective with a probability of more than 66%.

Overall, Fig. 2b indicates that the present influence of geophysical uncertainties on the spread in mitigation costs to achieve the 2 °C objective is comparable to that of the uncertainties arising from different future pathways for social development and technological changes and choices. The maximum difference in probability of staying below 2 °C between the least costly (blue-dashed) and the most costly (red-dotted) distribution is slightly greater than 60 percentage points. This roughly matches the range of probabilities found when taking into account the Earth system uncertainty under the same supply and demand assumptions (for example 0–70% for the entire range of carbon prices in our central case, which assumes a reference technology portfolio and intermediate energy demand). Such a finding is broadly consistent with earlier studies comparing the relative contributions of geophysical and technological factors[22] using a non-probabilistic approach.

Yet, despite all of the uncertainty in the geophysical, social and technological aspects, our analysis indicates that the dominant factor affecting the likelihood and costs of achieving the 2 °C objective is politics. Here we model political uncertainties by varying the timing of concerted global mitigation efforts. Although studies of the implication of delays in climate action are not new[2,23–26], our results show how geophysical uncertainties interact and compare with political inertia: if global temperature rise is to be kept below 2 °C with a probability of more than 66% under central technology and energy demand assumptions, our scenarios show that immediate and globally coordinated mitigation action is necessary (Fig. 2c; Supplementary Information provides an explanation of 'immediate'). Only for low-energy-demand pathways can global mitigation action be delayed until 2020 and the

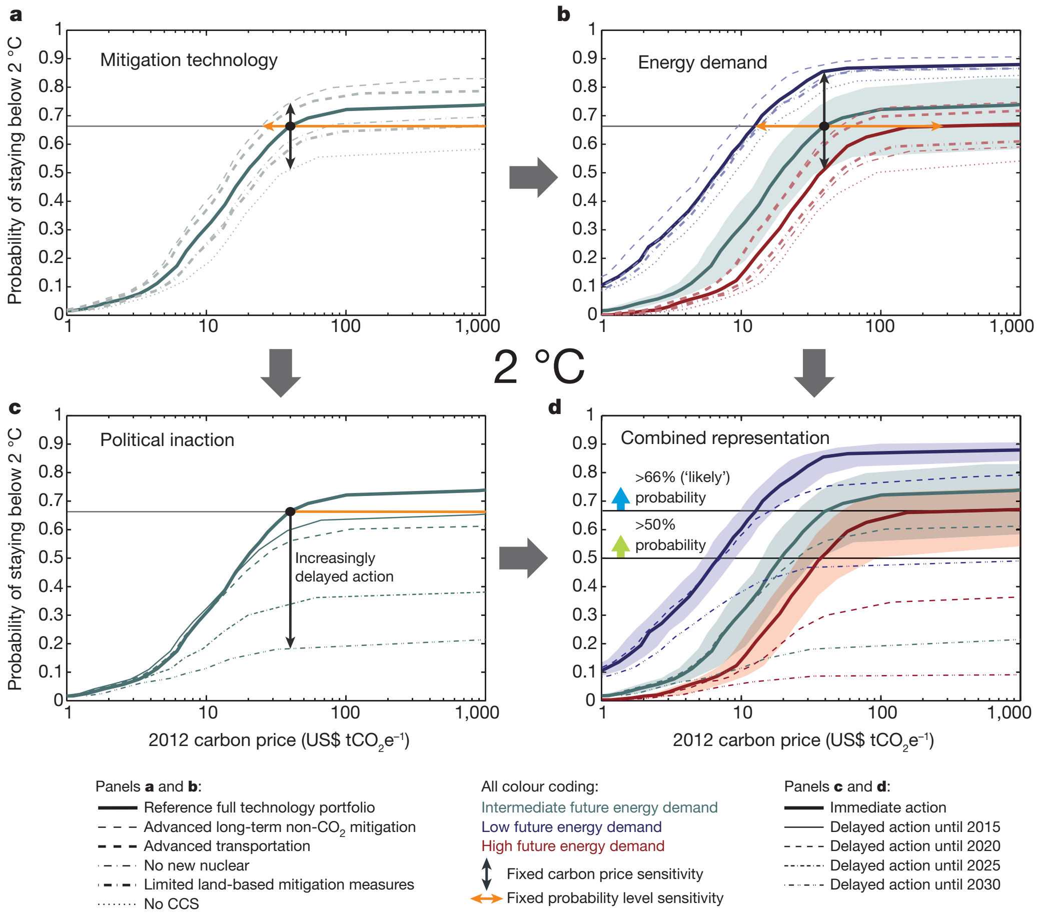

Figure 2 | Influence of mitigation technology, energy demand and political inaction on the cost–risk distributions for staying below 2 °C. Cost distributions for six cases with varying future availability of specific mitigation technologies (**a**) and three sensitivity cases for future energy demand (**b**, thick solid lines). Shaded areas and dashed lines in **b** represent technology-sensitivity cases comparable to those shown in **a**. Shaded areas and dashed lines in **d** represent technology- and politics-sensitivity cases comparable to those in **b** and **c**, respectively. **c**, Impact of delayed global mitigation action. **d**, Overview figure combining all sensitivity cases. The horizontal line in **a**–**c** is the 66% line. Similar figures for 2.5 and 3 °C are provided in Supplementary Figs 4 and 5. A comparison with 91 scenarios from the literature[2] is provided in Supplementary Fig. 7.

2 °C objective still be achieved with a probability of more than 66% (or delayed until 2030 with a probability of 50%; Fig. 2d).

In conclusion, we find that the effect of global mitigation action delayed by two decades is much more pronounced than the consequences of uncertainty surrounding mitigation technology availability and future energy demands, and renders even the geophysical uncertainties almost irrelevant for the 2 °C objective (Fig. 2d, Supplementary Table 2 and Supplementary Fig. 9). Furthermore, we find asymptotic limits to increasing the probability of reaching a given temperature objective in our model: if mitigation action is delayed, simply spending more money on the problem in the future will not increase this probability beyond certain limits imposed by the Earth system.

Our mitigation cost distribution methodology can also be applied to other temperature objectives, for example a weaker limit (3 °C) or a

Table 1 | Overview of sensitivity cases

	Mitigation technology
Technological limits	
No new nuclear	From 2020 onwards, no new investments are made into nuclear power, leading to a full phase-out of existing plants by 2060.
Limited land-based measures	The mitigation potential from biomass, land use and forestry is limited.
No CCS	Technology to capture and geologically store CO$_2$ (CCS) from fossil fuel and/or biomass energy never becomes available on a globally meaningful scale.
Technological breakthroughs	
Advanced transportation	Fundamental changes in transportation infrastructures (for example for electric transport) or major breakthroughs in transportation technology (for example in hydrogen fuel cells) lead to increased decarbonization of the transportation sector.
Advanced non-CO$_2$ mitigation	The mitigation potential of non-CO$_2$ greenhouse gases is assumed to improve continuously, beyond the level of current best practice.
	Energy demand
Intermediate demand	The development of energy demand and efficiency improvements is broadly consistent with (only slightly faster than) what is observed historically.
High demand	Energy efficiency improves more slowly than historically observed, leading to a high future energy demand.
Low demand	Energy efficiency improves radically in all end-use sectors (buildings, industry, transport) leading to low future energy demand.
	Political inaction
Delayed action	Globally concerted mitigation action is postponed from today until 2015, 2020, 2025 and 2030 in respective cases.

Detailed descriptions and background are provided in Supplementary Information and ref. 7.

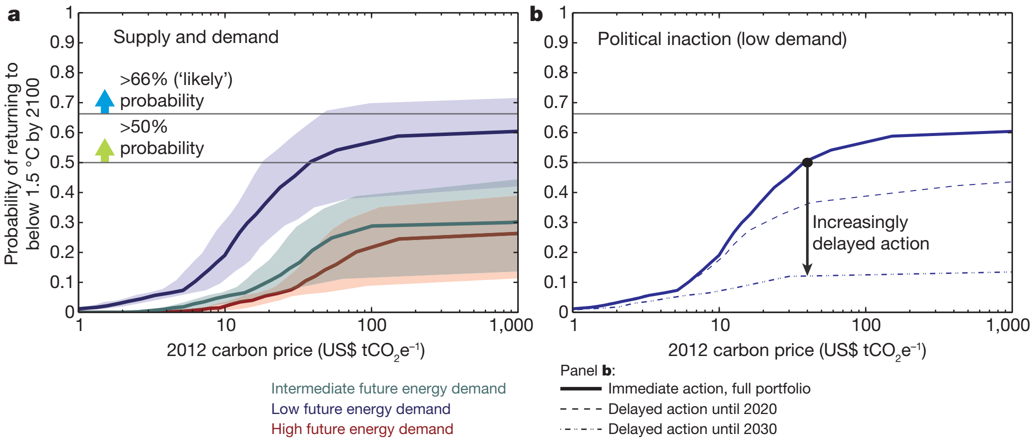

Figure 3 | Cost–risk distributions for returning global temperature increase to below 1.5 °C by 2100. a, Cost distributions for three cases of varying future energy demand (solid red, green, and blue lines) and varying future availability of specific mitigation technologies (shaded ranges around solid lines). Ranges show the variation over all assessed technology-sensitivity cases. **b**, Influence of global mitigation action delayed from now until 2030. The vertical axis shows the probability of returning global average temperature increase to below 1.5°C by 2100.

stricter limit (1.5 °C), the second of which has already been discussed in the policy arena[21]. We find that unless energy demand is low, CCS technology is available and global climate action is undertaken immediately, holding temperature increase to below 1.5 °C by 2100 with a probability of at least 50% is already unfeasible (Fig. 3a). In terms of costs, this would require the immediate introduction of global carbon prices of more than US\$40 tCO$_2$e^{-1} (increasing over time with the discount rate). If global mitigation action were delayed by 10 to 20 years, a carbon price of US\$40 tCO$_2$e^{-1} would yield probabilities of only 10–35%; and, even under higher prices, a 50% probability could no longer be reached under central technology and low-energy-demand assumptions (Fig. 3b). However, the same carbon price, US\$40 tCO$_2$e^{-1}, would prevent an increase in warming beyond 3 °C with a high probability (>90%) for all supply–demand combinations, contingent on the immediate global introduction of the pricing instrument (Supplementary Fig. 5).

Our findings have implications for the ongoing international climate policy discussions[27], which foresee a global agreement coming into effect only in 2020. For this delay strategy to be successful, national and local governments would need to place far greater importance on concurrent demand-side solutions to climate protection (thus lowering energy demand growth), as well as on voluntary or revised near-term mitigation policies and measures that anticipate and are consistent with a future stringent climate agreement. Our model results show that robustly safeguarding the future achievement of the oft-discussed 2 °C objective requires that society embarks on a higher-efficiency, lower-energy-demand course well before 2020 in the context of sustained, concerted and coordinated mitigation efforts.

METHODS SUMMARY

We create a large ensemble ($n > 700$) of emissions scenarios with MESSAGE[14,15], a global integrated assessment modelling framework with a detailed representation of greenhouse-gas-emitting sectors, by imposing cumulative constraints on greenhouse gas emissions (for all such gases: carbon dioxide, methane, nitrous oxide, halocarbons and fluorinated gases) of varying stringencies for the whole twenty-first century, and by changing salient features in the underlying scenario assumptions (see Supplementary Information, Supplementary Fig. 1, Supplementary Table 1 and ref. 7 for a full set of assumptions). Our scenarios assume 'middle-of-the-road' assumptions for socio-economic development from previous research on scenarios: population peaking at 9,700,000,000 later this century (United Nations median projection[28]) and gross world product increasing more than sevenfold by 2100 (updated Special Report on Emissions Scenarios B2 scenario projection by the Intergovernmental Panel on Climate Change[7,29]).

We then compute probabilistic estimates of global temperature increase for each scenario with the MAGICC climate model[16,17,30]. These estimates are based on a 600-member ensemble of temperature projections for each scenario, which together closely represent the carbon-cycle and climate uncertainties as assessed in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change[17]. Additionally, our temperature projections are also constrained by observations and estimates of hemispheric temperatures and ocean heat uptake (Supplementary Information). The probability of staying below a given temperature threshold is computed over the entire twenty-first century and relative to pre-industrial levels. In contrast to the 2 °C objective, the target of 1.5 °C is referred to as a long-term goal[21], meaning that we allow a small, temporary overshoot and assess the probability of returning warming to below 1.5 °C by 2100.

We present our results using carbon prices as the cost metric. For an illustration of our results using other cost metrics, such as total mitigation costs, see section 1.4 of Supplementary Information and Supplementary Figs 2 and 3. The carbon price shown is the price at the time action starts, discounted back to 2012 with a discount rate of 5% per year (Supplementary Information, section 1.4, and Supplementary Fig. 6).

Received 15 August; accepted 5 November 2012.

1. Randalls, S. History of the 2 °C climate target. *Clim. Change* **1,** 598–605 (2010).
2. Clarke, L. *et al.* International climate policy architectures: overview of the EMF 22 International Scenarios. *Energy Econ.* **31,** S64–S81 (2009).
3. Edenhofer, O. *et al.* The economics of low stabilization: model comparison of mitigation strategies and costs. *Energy J.* **31,** 11–48 (2010).
4. UNEP. *Bridging the Emissions Gap* 15–20 (United Nations Environment Programme, 2011).
5. O'Neill, B. C., Riahi, K. & Keppo, I. Mitigation implications of midcentury targets that preserve long-term climate policy options. *Proc. Natl Acad. Sci. USA* **107,** 1011–1016 (2010).
6. Core Writing Team, Pachauri, R. K. & Reisinger, A. (eds) *Climate Change 2007: Synthesis Report* (Intergovernmental Panel on Climate Change, 2007).
7. Riahi, K. *et al.* in *Global Energy Assessment: Toward a Sustainable Future* 1203–1306 (Cambridge Univ. Press, 2012).
8. Friedlingstein, P. *et al.* Climate–carbon cycle feedback analysis: results from the C4MIP model intercomparison. *J. Clim.* **19,** 3337–3353 (2006).
9. Meehl, G. A., Covey, C., McAvaney, B., Latif, M. & Stouffer, R. J. Overview of the coupled model intercomparison project. *Bull. Am. Meteorol. Soc.* **86,** 89–93 (2005).
10. Meehl, G. A. *et al.* in *IPCC Fourth Assessment Report* (eds S. Solomon *et al.*) 747–847 (Cambridge Univ. Press, 2007).
11. Meinshausen, M., Wigley, T. M. L. & Raper, S. C. B. Emulating atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 – Part 2: applications. *Atmos. Chem. Phys.* **11,** 1457–1471 (2011).
12. Archer, D. *et al.* Atmospheric lifetime of fossil fuel carbon dioxide. *Annu. Rev. Earth Planet. Sci.* **37,** 117–134 (2009).
13. Schaeffer, M., Kram, T., Meinshausen, M., van Vuuren, D. P. & Hare, W. L. Near-linear cost increase to reduce climate-change risk. *Proc. Natl Acad. Sci. USA* **105,** 20621–20626 (2008).
14. Rao, S. & Riahi, K. The role of non-CO$_2$ greenhouse gases in climate change mitigation: long-term scenarios for the 21st century. *Energy J.* **27,** 177–200 (2006).
15. Riahi, K., Gruebler, A. & Nakicenovic, N. Scenarios of long-term socio-economic and environmental development under climate stabilization. *Technol. Forecast. Social Change* **74,** 887–935 (2007).
16. Meinshausen, M., Raper, S. C. B. & Wigley, T. M. L. Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 – Part 1: Model description and calibration. *Atmos. Chem. Phys.* **11,** 1417–1456 (2011).

17. Rogelj, J., Meinshausen, M. & Knutti, R. Global warming under old and new scenarios using IPCC climate sensitivity range estimates. *Nature Clim. Change* **2,** 248–253 (2012).
18. Knutti, R. *et al.* A review of uncertainties in global temperature projections over the twenty-first century. *J. Clim.* **21,** 2651–2663 (2008).
19. Mastrandrea, M. D. *et al. Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties* 3 (Intergovernmental Panel on Climate Change, 2010); available at http://www.ipcc.ch/pdf/supporting-material/uncertainty-guidance-note.pdf.
20. Smith, S. M. *et al.* Equivalence of greenhouse-gas emissions for peak temperature limits. *Nature Clim. Change* **2,** 535–538 (2012).
21. UNFCCC. *FCCC/CP/2010/7/Add.1 Decision 1/CP.16* 3 (UN Framework Convention on Climate Change, 2010).
22. Smith, S. J. & Edmonds, J. A. The economic implications of carbon cycle uncertainty. *Tellus B* **58,** 586–590 (2006).
23. Vaughan, N., Lenton, T., &. Shepherd, J. Climate change mitigation: trade-offs between delay and strength of action required. *Clim. Change* **96,** 29–43 (2009).
24. den Elzen, M., van Vuuren, D. & van Vliet, J. Postponing emission reductions from 2020 to 2030 increases climate risks and long-term costs. *Clim. Change* **99,** 313–320 (2010).
25. Bosetti, V., Carraro, C., Sgobbi, A. & Tavoni, M. Delayed action and uncertain stabilisation targets. How much will the delay cost? *Clim. Change* **96,** 299–312 (2009).
26. Krey, V. & Riahi, K. Implications of delayed participation and technology failure for the feasibility, costs, and likelihood of staying below temperature targets: greenhouse gas mitigation scenarios for the 21st century. *Energy Econ.* **31,** S94–S106 (2009).
27. UNFCCC. *FCCC/CP/2011/9/Add.1 Decision 1/CP.17* (UN Framework Convention on Climate Change, 2011).
28. UN. *World Population Prospects: The 2008 Revision Population Database* (United Nations, 2009).
29. Nakicenovic, N. & Swart, R. *IPCC Special Report on Emissions Scenarios* (Cambridge Univ. Press, 2000).
30. Meinshausen, M. *et al.* Greenhouse-gas emission targets for limiting global warming to 2°C. *Nature* **458,** 1158–1162 (2009).

Supplementary Information is available in the online version of the paper.

Acknowledgements We thank V. Krey, P. Kolp and M. Strubegger for their support in developing the model set-up and extracting the results, R. Knutti and R. Socolow for comments and feedback during the writing process and S. Hatfield-Dodds, whose review comments substantially contributed to improving our manuscript. J.R. was supported by the Swiss National Science Foundation (project 200021-135067) and the IIASA Peccei Award Grant.

Author Contributions All authors were involved in designing the research. J.R. performed the research in collaboration with D.L.M. All authors contributed to writing the paper.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to J.R. (joeri.rogelj@env.ethz.ch).